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NONPERPENDICULAR ILLUMINATION OF ULTRASONIC CELLS

Report of Project MICHIGAN

By
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August 1966

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Willow Run Laboratories
THE INSTITUTE OF SCIENCE AND TECHNOLOGY
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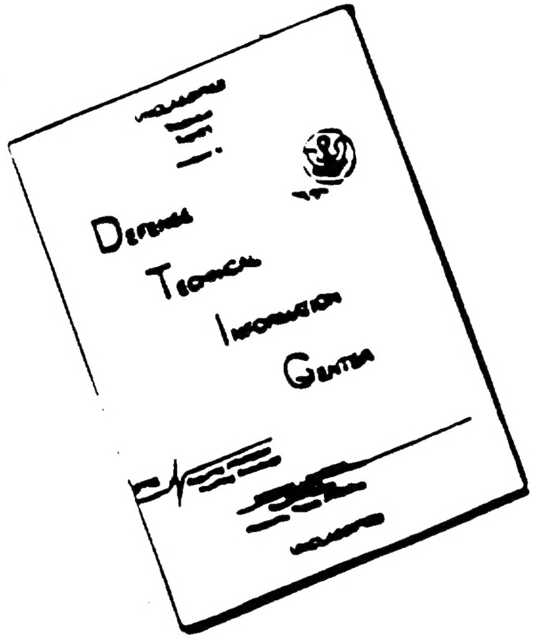

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NONPERPENDICULAR ILLUMINATION OF ULTRASONIC CELLS

Report of Project MICHIGAN

CONTRACT NO. DA-28-043-AMC-00013(E)

DA Project 1P6 20801 A 175 05

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For

U. S. ARMY ELECTRONICS COMMAND, FORT MONMOUTH, N. J.

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ABSTRACT

Results obtained by nonperpendicular illumination of ultrasonic cells are described. There is reasonably good agreement between theory and experiment; this agreement exists for results obtained when the cell is operated at 5, 15, and 25 Mc/s. In an optical analog computer, the light intensity of the optical output can be increased considerably by illuminating the cell at the Bragg angle; but this increase is obtained at the expense of decreased bandwidth of operation.

ULTRASONIC RADIATION

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FOREWORD

In accordance with recommendations of Project TEOTA (The Eyes of the Army), a large technical study made by the Army in 1952 on the problems of combat surveillance, Project MICHIGAN was established in May 1953 under a tri-service charter and under a contract administered by the U. S. Army Signal Corps. Its purpose was to perform research and development encompassing all problems pertaining to combat surveillance. The Project MICHIGAN contract essentially left the determination of the program to the Project itself. The Project was to determine the nature of the problems, the needs of the services, and the way the physical sciences could be used to meet these needs. A joint-services tactical and technical steering committee was established to provide broad guidance.

During the summer of 1953, Project MICHIGAN convened Project WOLVERINE, a summer study program to review the problems of combat surveillance and to recommend an initial program for Project MICHIGAN.

In February 1957, the U. S. Army Combat Surveillance Agency (USACSA) was established. At about this time, the tri-service charter and steering committee were terminated, and guidance of the project was assigned to USACSA. USACSA defined the role of Project MICHIGAN as complementary to the functions of the U. S. Army Signal Research and Development Laboratories and the U. S. Army Electronic Proving Ground. The "mission" of Project MICHIGAN has since been defined as follows: "To conduct a continuing long-range research and development program for advancing the Army's combat-surveillance and target-acquisition capabilities." With the reorganization of the Army in mid-1962, the technical cognizance of Project MICHIGAN shifted from the Office of the Chief Signal Officer to the U. S. Army Materiel Command (USAMC). Currently, technical guidance is provided by the Combat Surveillance and Target Acquisition Laboratory of the U. S. Army Electronics Command for USAMC.

The research and development effort of Project MICHIGAN is oriented toward achieving new and improved techniques which will lead to new or greatly improved combat-surveillance and target-acquisition equipment that will meet the long-range operational requirements of the Army in the field. Since 1953, the work of Project MICHIGAN has been concerned primarily with theoretical and experimental investigations to determine and to demonstrate the potential value of the many concepts and ideas for combat surveillance and target acquisition brought out in TEOTA and WOLVERINE and subsequently proposed by others including the Project itself. The cur-

rent emphasis is on the subjects of imaging radar, hologram radar, MTI radar, infrared-optical imaging and signal correlation techniques, and image interpretation.

The work reported upon was conducted under Subproject 1, Task 1, of the overall technical program for Project MICHIGAN approved by the Contracting Officer's Technical Representative under DA Project Number 1P6 20801 A 175, Task 05, "Airborne Surveillance Target Acquisition Radar Receiver, Recording and Display Techniques."

The Project is a part of a diversified program of research conducted for the Willow Run Laboratories of The University of Michigan's Institute of Science and Technology by a full-time staff of specialists in physics, engineering, mathematics, and related fields, by members of the teaching faculty, by graduate students, and by other research groups and laboratories of The University of Michigan. The function of the Institute of Science and Technology is to make available to government and industry the resources of The University of Michigan and to broaden the educational opportunities for students in the scientific and engineering disciplines.

The computations described in this report were performed by Mr. George Hurchalla and Mr. David B. Kirk of the Computation Department of the Willow Run Laboratories.

Progress and results described in reports are continually reassessed by Project MICHIGAN. Comments and suggestions from readers are invited.

CONTENTS

FIGURES

NONPERPENDICULAR ILLUMINATION OF ULTRASONIC CELLS

1. INTRODUCTION

The ultrasonic cell has long been used as a device for introducing a given input function into an optical analog computer for such purposes as spectrum analysis, filtering, and optical scanning. Modern technology has demanded more and more bandwidth in such devices, which, in turn, require the use of transducers with higher and higher resonant frequency. However, it has been shown [1] that at the higher frequencies the intensity of the desired optical output of such a computer decreases rapidly (with frequency) when the cell is illuminated with light which is perpendicular to the ultrasonic wave train. One possible solution to the problem of increasing the intensity of the output is to illuminate the cell at the Bragg angle, that angle at which all rays emitting from the cell are in phase.

2. THEORETICAL RESULTS

Figure 1 shows a general optical schematic in which collimated light is directed toward an ultrasonic cell of thickness L and length d. The ultrasound creates a phase grating in the cell, the Fourier transform of which is formed by the objective lens when the light is incident perpendicular to the ultrasonic wave train. The intensity of the light forming the central image I_0 (zero frequency), first-order images I_1 and I_1' (fundamental frequency), and higher harmonic images, all of which occur in a plane located a focal distance behind the objective lens, indicates the strength of these harmonics in the exciting signal.

Raman and Nath [2] performed one of the first analyses of the case in which the light is perpendicular to the ultrasonic wave train. By evaluating the diffraction integral across the face of the cell they found that the spectral images occur at an angle

$$\theta = \frac{n\lambda}{\lambda^*} \tag{1}$$

where θ = angle of inclination from the center line of the optical system

n = order of the harmonic frequency

λ = wavelength of the light

λ^* = wavelength of the ultrasound in the delay medium

and that the images have an intensity

$$\frac{I_n}{I_m} = \frac{J_n^2(v_t)}{J_m^2(v_t)} \tag{2}$$

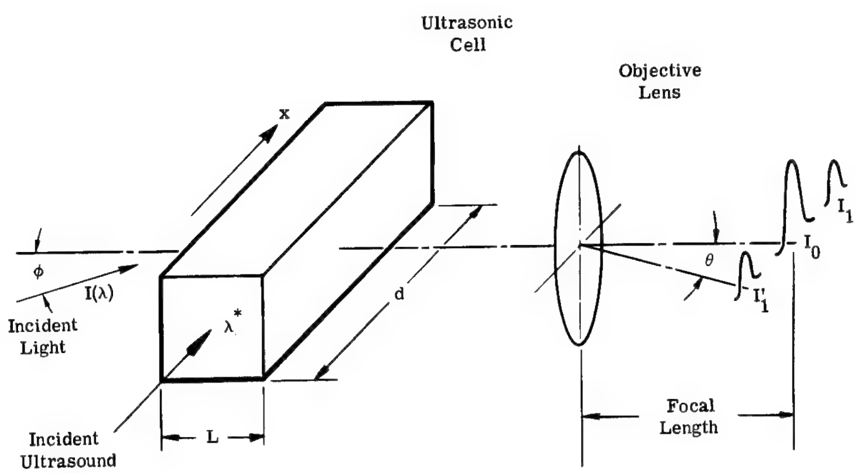


FIGURE 1. OPTICAL SCHEMATIC

where I_n = intensity of the nth harmonic

I_m = intensity of the mth harmonic

J_n and J_m = Bessel functions of the nth and mth orders

$$v_t = \frac{2\pi\mu L}{\lambda} \tag{3}$$

μ = alternating portion of the index of refraction

The above relations describe what is known as normal diffraction, i.e., diffraction in which the ultrasonic wavelength is long, and the value of μ is small.

Willard [3] has expressed a criterion for distinguishing normal from abnormal diffraction. He suggested that the value of the product

$$K = \frac{Lf^2 v_t}{2\pi} \tag{4}$$

where f = acoustic frequency of operation

provides a working distinction between normal and abnormal Bragg diffraction. He used the value 34.4 Mc/s^2-cm as a criterion. If K is less than this number, the diffraction is normal; but if K is greater, the diffraction is abnormal. In common practice, the use of 10 Mc/s or less results in normal diffraction; the use of more than 10 Mc/s results in abnormal diffraction. Abnormal diffraction occurs when I_1 and I_1' (fig. 1) do not occur simultaneously with equal strength. Hargrove [4], and other investigators, considered the abnormal cell as a series of normal cells. He introduced the parameters

$$Q_\ell = \frac{2\pi\lambda\ell}{\mu_\lambda^{*2}} \qquad \text{and} \qquad V_\ell = \frac{2\pi\mu\ell}{\lambda} \tag{5}$$

where Q_ℓ = a constant for the individual layer

ℓ = thickness of the individual layer

μ_0 = index of refraction

V_ℓ = the incremental phase change in the individual layer

and stated that $Q_\ell V_\ell << 2$ for normal diffraction.

Klein [5] achieved a considerable simplification of Hargrove's results and, among others, used the parameter

$$\alpha = -\mu_0 \frac{\lambda^*}{\lambda} \sin \phi \tag{6}$$

where α = an angular constant

ϕ = angle of incidence measured from the normal

A value of $\alpha = \frac{1}{2}$ is equivalent to the Bragg angle.

The program, as defined by Klein, was set up for the IBM-7090 computer to obtain theoretical predictions which could be compared with experimental results obtained earlier. During the computation, a most interesting phenomenon was noted; namely, that when the ultrasonic cell was illuminated at the Bragg angle, the ratio of I_1/I_0 was independent of frequency. This result, which is shown in figure 2, was also noted and experimentally verified by Klein [6].

3. EXPERIMENTAL PROGRAM

3.1. EQUIPMENT USED

The optical arrangement for the experimental program is shown in figure 3. A filtered 5461-Å lamp was used as a light source. A set of 75-mm, f/2.8 lenses was used as a condenser. The output of the last lens was focused on a 25-μ-diam aperture, thus simulating a point source, the output of which was collimated by a 100-mm, f/2.3 lens. The output from this lens constituted the incident light $I(\lambda)$ of figure 1. The angle of illumination was varied by changing the position of the light-source section, shown mounted on a wooden platform in the figure, and was calculated from the dial-gauge reading.

The faces of the ultrasonic cell were of optical-quality glass, polished flat to 1/8 wavelength. The internal dimensions of the cell were 7/8 × 7/8 × 2-in long. A rubber ultrasound absorber was cemented to the end of the cell opposite the transducer.

All transducers were X-cut quartz crystals. Most were 1/2-in in diameter, with a 3/8-in-diam gold electrode evaporated on one side and a 1/2-in-diam gold electrode evaporated on the other side. However, some crystals were smaller in diameter.

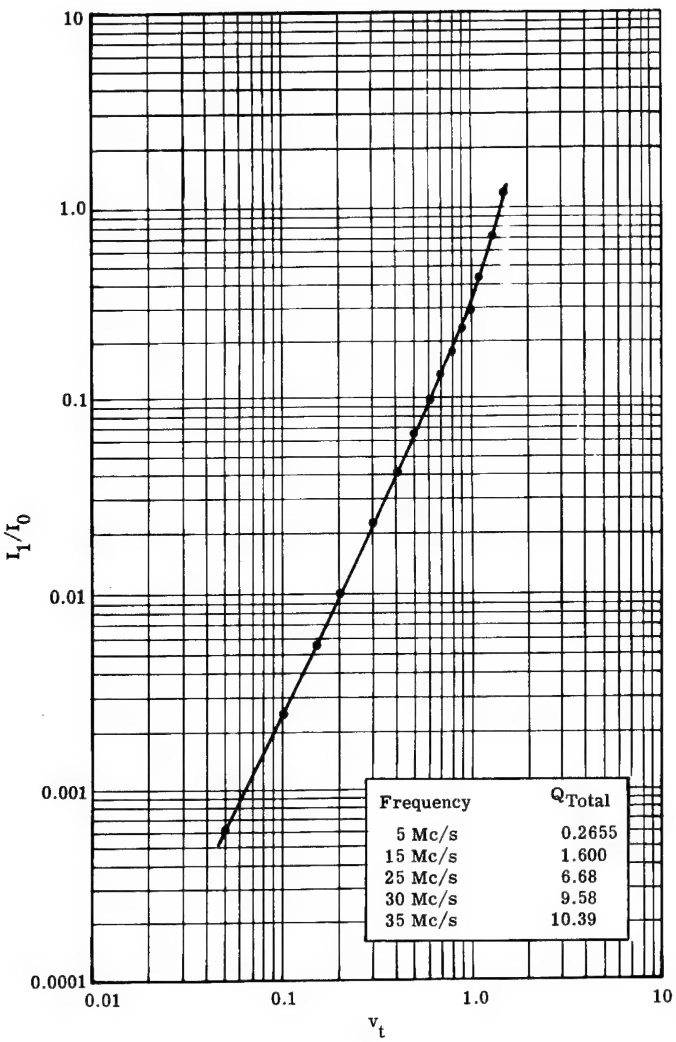


FIGURE 2. BRAGG-ANGLE ILLUMINATION OF ULTRASONIC CELLS ($\alpha = 1/2$)

Crystals with fundamental resonant frequencies of 5, 15, and 25 Mc/s were used. The crystals were mounted onto a plastic holder which had a 3/8-in hole drilled so that the inner electrode was accessible for electrical connection; therefore, the backing impedance of the crystals was air.

The light beam was directed through the ultrasonic column, far enough from the transducer to avoid local transducer disturbances, but close enough to minimize ultrasonic attenuation losses. Then the optical output from the ultrasonic cell was brought to a focus with a 152-mm, f/2.7 lens. Finally, the intensity of the spectral images was measured with a specially constructed and dc-operated photomultiplier circuit which has shown excellent stability.

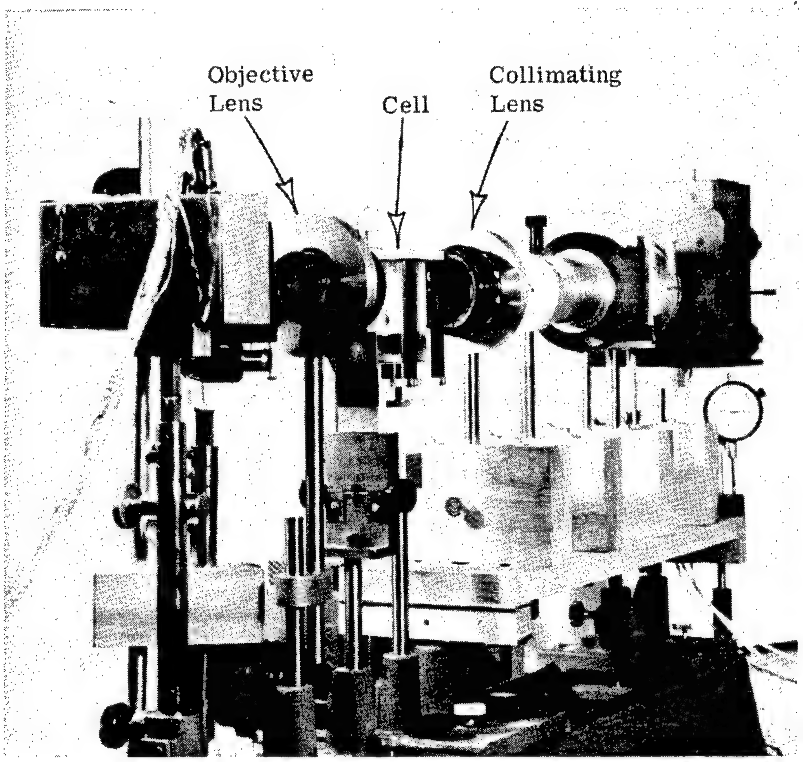
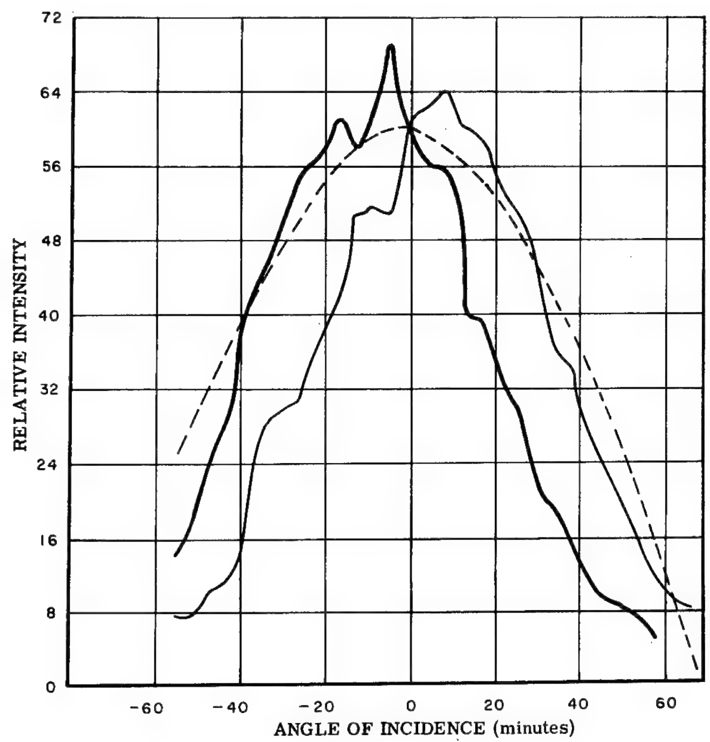


FIGURE 3. ARRANGEMENT OF OPTICAL EQUIPMENT

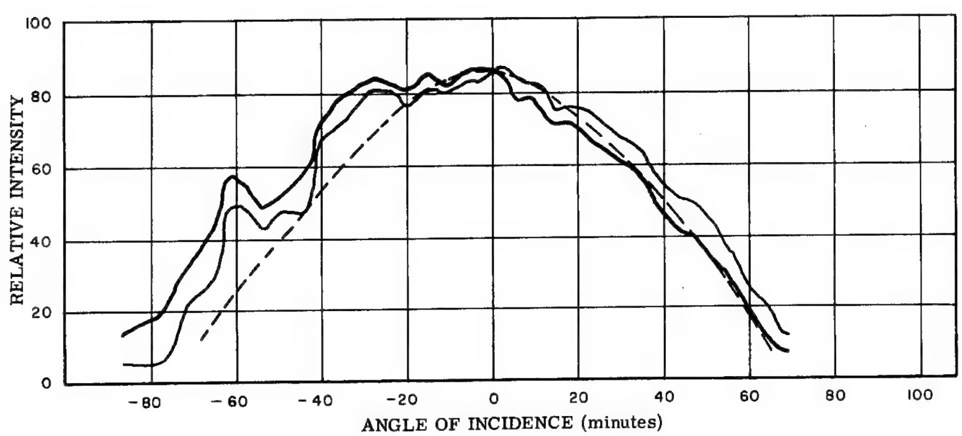
3.2. EXPERIMENTAL RESULTS

The experimental results are given in figures 4 through 6, which show the relative intensity of the first-order diffraction image as a function of the angle of incidence. In these figures, three curves are shown: The heavier line is the intensity of one first-order image (I_1 in fig. 1), the lighter line is the intensity of the other first-order image (I_1' in fig. 1), and the broken line is the computed result for I_1. Figure 4 shows the results for a transducer with a resonant frequency of 5 Mc/s, figure 5 shows the results for 15 Mc/s, and figure 6 shows the results for 25 Mc/s.

One result which is immediately evident from these tests is that, at 25 Mc/s and, undoubtedly, at higher frequencies, considerably more light is available when the cell is illuminated at the Bragg angle than when it is illuminated at an angle perpendicular to the ultrasonic wave train (the angle at which the two curves I_1 and I_1' intersect).



(a)



(b)

FIGURE 4. RELATIVE INTENSITY OF FIRST-ORDER DIFFRACTION VS. ANGLE OF INCIDENCE FOR OPERATION AT 5 Mc/s. (a) 60 V. (b) 100 V.

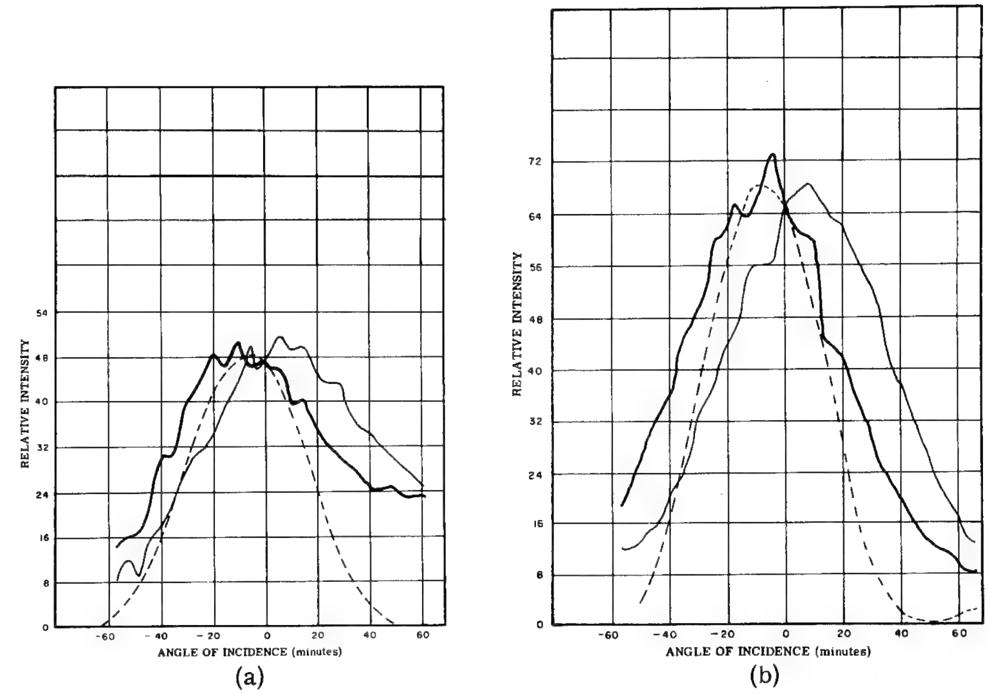


FIGURE 5. RELATIVE INTENSITY OF FIRST-ORDER DIFFRACTION VS. ANGLE OF INCIDENCE FOR OPERATION AT 15 Mc/s. (a) 40 V. (b) 60 V.

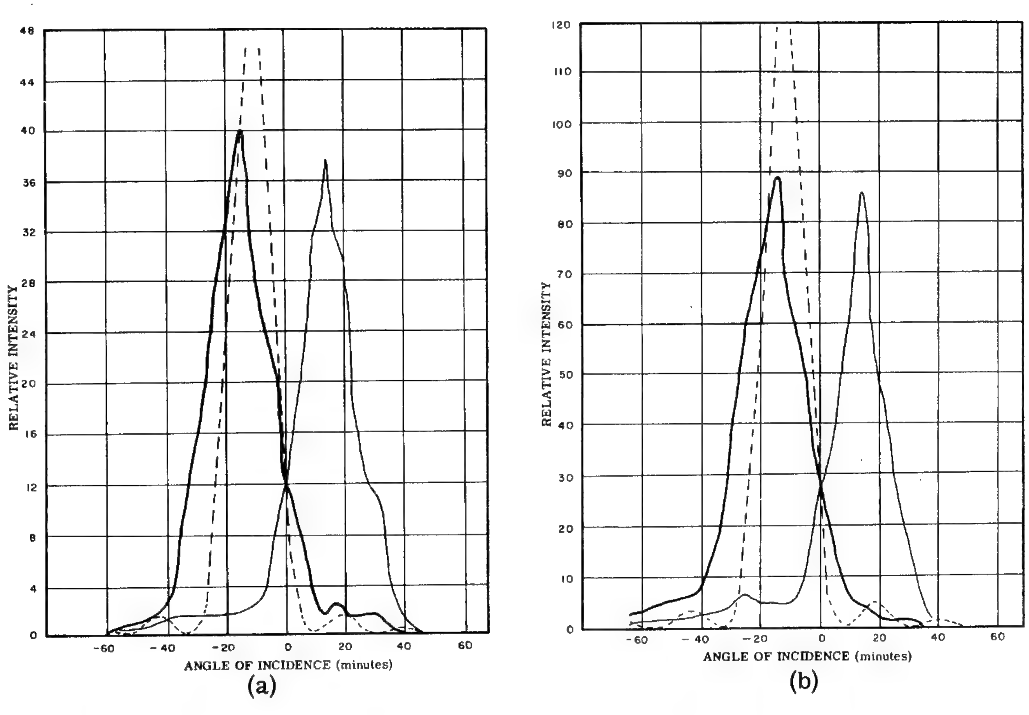


FIGURE 6. RELATIVE INTENSITY OF FIRST-ORDER DIFFRACTION VS. ANGLE OF INCIDENCE FOR OPERATION AT 25 Mc/s. (a) 30 V. (b) 50 V.

4. DETERMINING THE THEORETICAL-RESULTS CURVES

The theoretical results, shown by the broken line in figures 4 through 6, were computed in the following manner: The computer program for the theoretical solution was defined by three parameters, v_t (eq. 3), Q (eq. 5), and α (eq. 6). In essence, we specified a value of v_t, which gives the driving voltage; a value of Q, which essentially gives the operating frequency (for a specific ultrasonic cell); and a value of α, which gives the angle of illumination, once the other operating conditions are established.

An experimental curve, in which I_1/I_0 was plotted as a function of electrical voltage, was determined, with the ultrasonic wave train perpendicular to the light beam ($\alpha = 0$). And a theoretical curve in which I_1/I_0 was plotted as a function of v_t was determined ($\alpha = 0$). Then, by matching values of I_1/I_0 from the two curves, an operating value of v_t was determined. (In the latter curve, the value of Q was adjusted for the cell dimensions and operating frequency of the experimental curve.) Using the operating value of v_t, we determined a theoretical curve in which I_1/I_0 was plotted as a function of α, and we adjusted the intensity value of the curve, where $\alpha = 0$, to indicate the theoretical relative intensity at other angles of illumination. This information was then plotted as the broken line shown in figures 4 through 6.

5. DISCUSSION OF RESULTS

A comparison of the computed curve with the experimentally obtained curves (figs. 4 through 6) indicates that good agreement exists between theory and experiment, with the possible exception of the results at 25 Mc/s; here, the theoretical intensity far exceeds the experimental intensity. It is believed that this discrepancy was caused by experimental error. However, there is a much more important aspect of these results which should be discussed: that aspect is the ratio of light intensity obtained when the cell is illuminated at the Bragg angle to the intensity obtained when the cell is illuminated perpendicularly to the ultrasonic wave train. Further, the effects of these two types of illumination on the bandwidth that may be achieved under the same conditions must be considered. From table I, it is obvious that at frequencies below 25 Mc/s (Q = 6.68), there is little to be gained in light intensity by illuminating at the Bragg angle.

Let us now consider the bandwidth available. This may be calculated from the expression

$$\alpha = -\mu_0 \frac{\lambda^*}{\lambda} \sin \phi$$

from which

$$\Delta\alpha = -\mu_0 \frac{\Delta\lambda^*}{\lambda} \sin \phi$$

TABLE I. COMPUTED I_1/I_0 FOR ILLUMINATION AT BRAGG ANGLE COMPARED WITH COMPUTED I_1/I_0 FOR ILLUMINATION PERPENDICULAR TO WAVE TRAIN

Frequency (Mc/s)	Voltage (rms)	I_1/I_0 for Illumination at Bragg Angle (A)	I_1/I_0 for Illumination Perpendicular to Wave Train (B)	Ratio $\left(\frac{A}{B}\right)$
5	60	0.0447	0.0449	1.0
5	100	0.1119	0.1120	1.0
15	40	0.0237	0.0225	1.05
15	50	0.0333	0.0317	1.05
15	60	0.0459	0.0437	1.05
25	30	0.42	0.109	3.85
25	40	0.712	0.149	4.76
25	50	0.999	0.166	6.03

From the computed data, $\Delta\alpha$, $\Delta\lambda^*$, and the bandwidth can be determined. Since light intensity is analogous to power, the available bandwidth can be determined as that difference in ultrasonic wavelength which produces a change in α sufficient to decrease the value of I_1 to 0.5 of I_1 when $\alpha = 0$ (see table II).

It is easily seen that the increase of usable light achieved by illuminating at the Bragg angle is obtained at the cost of drastically decreasing the available bandwidth. This decrease in bandwidth is independent of that which usually occurs because of difficulties inherent with crystal transducers. However, it should be borne in mind that these bandwidth results are calculated

TABLE II. AVAILABLE BANDWIDTH WHEN ILLUMINATING AT THE BRAGG ANGLE (0.500 criterion)

Frequency (Mc/s)	Band Limits: f_1 to f_2* (Mc/s)	Bandwidth (Mc/s)
15	11.12 to 23.1	11.98
25	23.4 to 26.8	3.4

*$f_1 < f_0 < f_2$ where f_1 = lower band limit

f_0 = resonant frequency

f_2 = upper band limit

and have not been verified experimentally. Nevertheless, since there has been excellent theoretical-experimental agreement throughout the program, it is felt that these conclusions bear merit.

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13. ABSTRACT

Results obtained by nonperpendicular illumination of ultrasonic cells are described. There is reasonably good agreement between theory and experiment; this agreement exists for results obtained when the cell is operated at 5, 15, and 25 Mc/s. In an optical analog computer, the light intensity of the optical output can be increased considerably by illuminating the cell at the Bragg angle; but this increase is obtained at the expense of decreased bandwidth of operation.

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